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INVESTIGATION OF THE MINING DEPARTMENTS INFLUENCE OF SOLOTVYNSKY SALT MINE SE ON THE EARTH SURFACE, BUILDINGS AND CONSTRUCTIONS USING SATELITE RADAR MONITORING

The most dangerous exogenous geological processes (EGP) in terms of the amount of damage caused to economic objects include: landslides, karst, flooding, abrasion, mudslides, etc. The distribution and intensity of EGP are determined by the peculiarities of geological and geomorphological structure of the territory, its tectonic, neotectonic and seismic regime, as well as hydrological, climatic, hydrogeological paleo- and modern conditions. Solotvynsky salt mine is one of the oldest enterprises in Transcarpathia. The field has been exploited since the Roman Empire. In 1360, a settlement of salt miners, Solotvyno, was founded on the site of the mine, which later became a center of salt production and a royal monopoly. There are a total of nine mines in the field. In 1995–1996 and 2001, floods began flooding mines. In 2005, landslides and karst abysses intensified in Solotvyno, leading to damage to residential buildings, roads and infrastructure. There was a complete flooding of the mines of two mines. Currently, dangerous natural and man-made processes are observed on the territory of the salt mine and adjacent territories. This is mainly salt karst, both underground and surface, the collapse of areas in the location of mines, as well as landslides. Therefore, the purpose of the research is to conduct a geodynamic audit of SOLOTVYNSKY SALT MINE SE and the surrounding area with the possibility of identifying areas with subsidence or rise of the earth's surface, which are gradually slowing down, accelerating or developing at a constant rate. Output data. Radar interferometry data in the period from April 30, 2016 to June 25, 2018 were used for research and performance of geodynamic audit of SOLOTVYNSKY SALT MINE SE and the adjacent territory. Modern methods of interferometric processing of satellite radar data are used in the work: the method of "PS" – the method of constant scatterers, and the method SBAS – the method of small baselines. The method of geometric leveling was used to measure vertical displacements in some places on the earth's surface in order to verify interferometric data. Monitoring of the area of interest was carried out using modern technologies of satellite radar interferometry. According to the results of observations of landslides and individual objects by space (radar interferometry) and ground (geometric leveling) methods, a high correlation of data was recorded and the presence of zones of active subsidence in the mining area was confirmed.

Key words: remote sensing; radar interferometry; vertical displacements of the earth's surface; PS and SBAS methods; geometric leveling; monitoring.

Introduction

The problem of assessing the nature of changes in the earth's surface becomes relevant in the context of enhanced development of urban areas. The monitoring of vertical landslides for areas with mining is of particular importance. Geodetic methods (*method of geometric leveling, GNSS measurements, etc.*) of observation of the earth's surface deformations today are time consuming, and in some cases dangerous. Such circumstances do not allow to apply them in full and, as a rule, on all zone of researches, even, in small territories. An alternative to these methods is the use of radar spacecraft and interferometric data processing methods. The advantages of this technology are: observation of deformations of the earth's surface in large areas with minimal time and money, efficiency, rapid collection of cartographic information and, the most importantly, the ability to obtain measurements in the past through the use of archival images. This method is completely safe because it uses only satellite radar data and does not require field work. Massive use of satellite radar data in the last 6 years has become possible only with the advent of the European Space Agency's (ESA)

Copernicus program and Sentinel-1 spacecraft (a, b) data, which are publicly available. Using the availability of radar imaging of Sentinel-1a and Sentinel-1b spacecraft, it has become possible for most researchers to quantify the Earth's motion in both the vertical and east-west directions, combining radar scanning data obtained from satellite flight from south to north and north southward. The use of radio waves allows radar systems to monitor, for example, deformations of the earth's surface, despite the clouds and time of day. This technology, being integrated into the classical system of surveying and geodetic observations, will regularly obtain models of vertical landslides. The information obtained on the basis of radar processing will serve as a basis for organizing a more detailed study of the territory and forecasting the geodynamic situation. This set of measures is designed to increase the level of industrial safety during mining operations at the operated subsoil facilities.

Analysis of recent research and publications related to solving this problem.

The technical capability of SAR was demonstrated earlier, and this technology gained widespread popularity in the early 1990s due to successful observations of soil deformation caused by the Landers earthquake in California [Berardino, et al., 2002] and the movement of ice cover in the Antarctic region [Gabriel, et al., 1989]. Radar imaging is one of the types of aerospace imaging, which is performed using radar, an active microwave sensor capable of emitting and receiving scattered polarized radio waves in certain ranges of wavelengths (frequencies) [Gabriel, et al., 1989]. The feedback signal contains information about the physical and geometric properties of the surface [Giff, et al., 2008]. In the EU, especially in Italy, national monitoring of landslides and subsidence in coal mines according to satellite radars COSMO-SkyMed (CSM), TerraSAR-X (TSX), TanDEM-X (TDX), Sentinel-1 (a, b) based on the technology of permanent interferometric reflectors (PS) is organized. The Norwegian Geological Survey (NGU), the Norwegian Water and Energy Administration (NVE) and the Norwegian Space Center have launched InSAR Norway, the first nationwide and free online mapping service for InSAR data. The service has made InSAR data available throughout Norway. The NORUT Research Institute was instrumental in creating a system for monitoring the earth's surface and objects using satellite data from the Sentinel-1 spacecraft (a, b). Radar interferometry according to Sentinel-1 allows to perform space-time observations with high resolution (for example, a dense network of measuring points) in large areas, and to track and display the dynamics of current processes due to frequent repetition times of the satellite (to study the dynamics of deformation changes) [Strozzi, et al., 2013; Elliott, et al., 2016; Li, et al., 2016].

Statement of the problem. Solotvynsky Salt Mine SE, which is administratively located in Tyachiv district of Zakarpattia region, contains the eponymous rock salt deposit, which is one of the largest deposits in Ukraine. From the mid-90s of the last century, problems began to arise in its functioning mines, which led to a dangerous ecological situation of man-made nature. In 2007 Solotvynsky Salt Mine SE, ceased its rock salt production, and the underground department of the Ukrainian Allergy Hospital was closed. The situation has deteriorated and since 2010 reached the state level (***expert opinion of the Ministry for Emergencies of Ukraine dated 09.12.2010 No. 02-17292/165***). In 2013, Solotvyno was declared a zone of emergency of national importance.

The results of research [Szűcs, et al., 2021] show that despite the huge risk management efforts, the risk area continues to expand at a maximum rate of 5 cm/year. Observations of deformations for 4.5 years did not show a slowdown. And currently, the situation is very difficult, the subsidence continues, new failures are formed, which threaten the safety of people. All these processes indicate that the situation in Solotvyno remains unstable and requires, first of all, an objective geodynamic assessment and, further, constant and reliable monitoring of the earth's surface deformation. This set of measures will help in making management decisions to stabilize the territory in the future, in order to safely use it as a tourist recreation area, and eventually possibly as an enterprise for salt production.

Materials and methods

Interferometry is one of the methods of radar imaging (***RI***), which captures the amplitude and phase of the reflected signal. One image obtained using synthesized aperture radar (***SAR***) is mostly of no practical value, while two images (***interference pair***) taken at different angles can be used to build a digital terrain model [Gabriel, et al., 1989].

Regarding radar imaging, the orientation of the baseline along or perpendicular to the direction of movement of the radar with synthesize daperture (RSA) determines the type of interferometric measurements, so there is a longitudinal and transverse interferometry. The technology of longitudinal interferometry is based on measurements carried out in a plane parallel to the motion of the RSA carrier. In this case, the signal processing is obtained simultaneously from two antennas located along the line of the radarmovement. Such measurements allow you to detect moving objects on the background of the underlying surface and measure their speed. For transverse interferometry, two or more antennas must be located in a plane perpendicular to the direction of movement of the RSA carrier. The joint processing of phase information received by two antennas simultaneously or over a period of time allows to reproduce the relief of the underlying surface or to calculate the displacements (vertical and from south to north and from north to south) of the earth's surface and objects.

Interferometric processing combines complex images recorded by antennas at different viewing angles or at different times. According to the results of comparing two images of the same area, an interferogram is obtained, which is a network of colored bands, the width of which corresponds to the phase difference of both exposures. Interferometry is an alternative to traditional stereophotographic technology for creating topographic maps with high spatial resolution, independent of weather conditions and time of day during shooting [Fanti, et. al., 2013].

Each point of the complex image can be described in general by a function of the form:

$$F\,(x,y) = I(x,y) * e^{i\varphi\,(x,y)} \qquad (1)$$

where I is the intensivity of the signal, which falls on the point; φ is the phase of the point; x, y are the coordinates of the point.

“Multiplication” of images at each point gives:

$$T\,(x,y) = F_1(x,y) * F_2^*(x,y) = I' * e^{i\Delta\varphi\,(x,y)}$$ w here I' the interfometric intensivity of the point; * is the complex connection; $\Delta\varphi\,(x,y)$ is the interfometric phase.

The phase difference between two points on the interference pair is proportional to the travel difference $2(r_0 - r_1) = 2\Delta r$ (the coefficient 2 indicates the double passage of the path by the waves) and equals $4\Delta r\pi/\lambda$, where λ is the wavelength.

Fig. 1 shows the positions of two RSA carriers (S_1 and S_2) and their parallel (B_r) and normal (B_n) offset relative to the line of observation. The location of two points of the section P_1 and P_2 and their displacements – normal n_P and parallel r_P relative to the line of observation are also indicated.

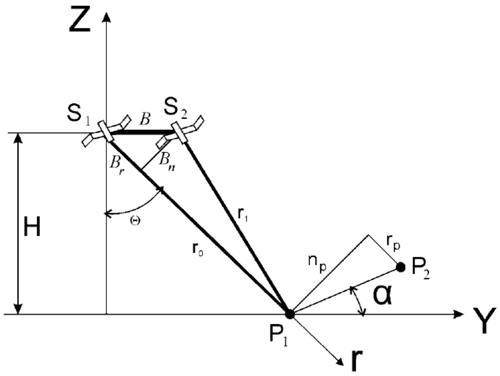

Fig. 1. Diagram of the location of the RSA during interferometric measurements

The main will be the position of the sensor S_1 with the corresponding point P_1 with the distance between them r_0. When you change the position of the RSA, the distance between the surface and the sensor will change to:

$$r = \sqrt{(r_0 + r_\rho - B_r)^2 + (n_\rho - B_n)^2}, \qquad (2)$$

In the case where the distance between the two antennas S_1 and S_2 is small compared to r_0, you can record the change in the interferometric phase in an approximate form:

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta(\Delta r) = \frac{4\pi B_n n_\rho}{\lambda r \text{Ç}}, \qquad (3)$$

This result allows us to conclude that if we know the relative displacement of the two orbits to the line of observation B_n, the distance r_0 and the wavelength used during the location, then the value of Δφ depends only on n_P.

Therefore, the phase interference image is a map of the relative elevation of the landscape along the line of observation. After some transformations, equation (3) can be rewritten as:

$$\Delta\varphi = \frac{4\pi B_n q}{\lambda r \text{Ç} \sin\theta} = 2\pi \frac{q}{q \text{Ç}}, \qquad (4)$$

Where q=Δzis the relative increase; $q = \frac{2B_n}{\lambda r \text{Ç} \sin\theta}$.

Since there are some sources of errors in radar data (*temporal and geometric decorrelation*, *atmospheric signal delay, etc.*), there are a number of methods of differential interferometric processing of time series, which in turn weaken the influence of these sources of errors [Ferretti, et al., 2019]. Given that the study area is built-up and covered with vegetation, the method of permanent scatterers (PS) and the method of small baselines (SBAS) [Berardino, et al., 2002] were used, the features of which are given below (*multi-pass radar interferometry technology*).

PS processing is generally considered more reliable because it uses 30 or more images of the same area on different dates, taken in the same satellite radar survey geometry, so the accuracy of displacement can reach several millimeters. The main purpose of permanent diffuser (*PS*) technology is its application in built-up areas. This method focuses on a subset of points that demonstrate relatively constant scattering properties over time. Due to the dominance of the reflection of these point scatterers in the cell of spatial resolution of the image, the effect of geometric decorrelation is also greatly reduced. Interferograms are formed by recombination of reordered SLC images. To reduce the effect of geometric decorrelation, the interferogram is first filtered by azimuth to exclude a non-overlapping Doppler spectrum. This reduces the component of this noise figure in the time series of deformations of permanent diffusers (*PS*).

For PS, the SBAS method is less sensitive to the number of images because it uses spatially distributed coherence instead of considering only individual points, as in PS. With the help of small baselines, both the geometric and temporal decorrelation effect is reduced. Due to the small baselines and multi-visibility of image pixels that are often used, the SBAS approach is particularly suitable for distributed scattering mechanisms that occur in rural regions with unsown areas [Feoktistov, et al., 2015].

However, in general, it should be noted that the more images, the better the quality of the results. This is because the atmospheric component can be better estimated and reduced. In terms of determining the function of displacements of points on the earth's surface, SBAS is not limited to linear: in fact, in addition to linear, quadratic and cubic models are supported.

Research results

This article presents the results of research on adaptation of existing radar methods of deformation monitoring using space radar interferometry, in relation to the territories of liquidated mines of Solotvynsky Salt Mine SE taking into account the specifics of the deformation surface. The area of interest is presented on Fig. 2.

During the period from April 30, 2016 to June 25, 2018, we performed processing of satellite radar survey of Sentinel-1a, Sentinel-1b spacecraft (*Interferometric Wide Swath mode, VV polarization, interferometric orbit No. 131*) on the territory of Solotvynsky Salt Mine using the ENVI licensed software package and the SARScape module. Table 1 shows a list of used radar space images of the Sentinel-1 spacecraft (a, b) – 64 images.

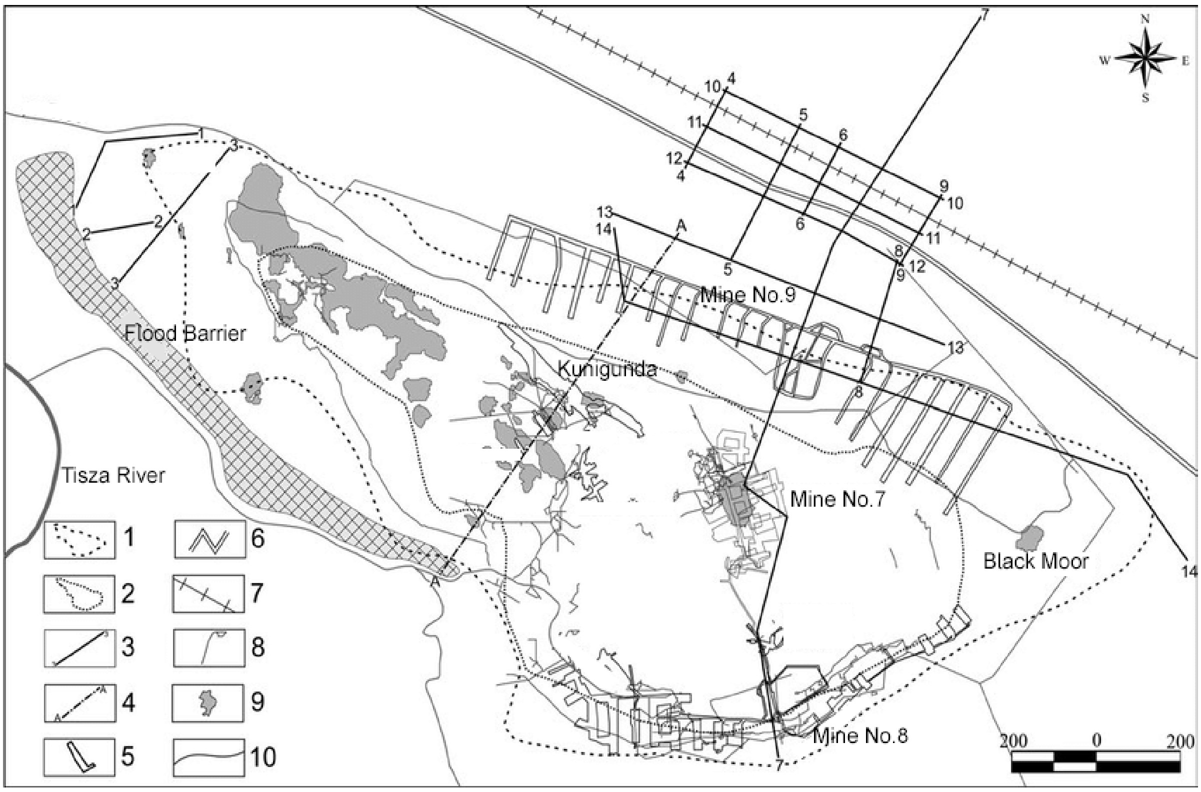

Fig. 2. Scheme of Solotvyno rock salt deposit – research area

Table 1

List of Sentinel-1 spacecraft images used in the work (a, b)

No.	Date	**No.**	Date	**No.**	Date	**No.**	Date
1	30.04.2016	17.	19.04.2017	33.	24.07.2017	49.	27.03.2018
2	12.05.2016	18.	25.04.2017	34.	30.07.2017	50.	02.04.2018
3	24.05.2016	19.	01.05.2017	35.	05.08.2017	51.	08.04.2018
4	05.06.2016	20.	07.05.2017	36.	11.08.2017	52.	14.04.2018
5	29.06.2016	21.	13.05.2017	37.	17.08.2017	53.	20.04.2018
6	11.07.2016	22.	19.05.2017	38.	23.08.2017	54.	26.04.2018
7	23.07.2016	23.	25.05.2017	39.	29.08.2017	55.	02.05.2018
8	04.08.2016	24.	31.05.2017	40.	04.09.2017	56.	08.05.2018
9	16.08.2016	25.	06.06.2017	41.	10.09.2017	57.	14.05.2018
10	28.08.2016	26.	12.06.2017	42.	16.09.2017	58.	20.05.2018
11	09.09.2016	27.	18.06.2017	43.	22.09.2017	59.	26.05.2018
12	21.09.2016	28.	24.06.2017	44.	28.09.2017	60.	01.06.2018
13	03.10.2016	29.	30.06.2017	45.	10.10.2017	61.	07.06.2018
14	15.10.2016	30.	06.07.2017	46.	16.10.2017	62.	13.06.2018
15	27.10.2016	31.	12.07.2017	47.	22.10.2017	63.	19.06.2018
16	07.04.2017	32.	18.07.2017	48.	28.10.2017	64.	25.06.2018

The technology of multi-pass radar interferometry is used in the work: interferometric analysis by SBAS method, which allows us to build interferograms of the whole area, and point analysis of constant reflectors by PS method, the results of which are a map of vertical movements of the earth's surface and objects. The public digital terrain model SRTM is used as a reference relief. The accuracy of interferometric measurements was: the standard deviation (*average speed of vertical displacements in the radar measurement*) by the PS method does not exceed 2 mm/year, by the SBAS method does not exceed 11 mm/year.

The PS method identified a total of 2957 permanent reflectors (*places of radar measurements*) of the radar signal (*highly coherent objects: buildings, structures, highways and railways, stone dumps, quarries, areas of open ground, etc.*). In operation, stable objects are objects whose velocity of vertical displacements are in the range (–8… +8 *mm/year*). At 329 points, subsidence was recorded, the maximum speed of which is up to –39 mm/year. The SBAS method identified a total of 1130 permanent reflectors of the radar signal (*coherent objects: stone dumps, quarries, areas without vegetation*), in which the maximum subsidence was up to –127 mm/year.

According to the results of interferometric processing of retrospective radar data, almost throughout the study area, stable deformation characteristics, namely time series of vertical displacements of the earth's surface, buildings and structures, separately calculated average velocities of vertical displacements (*mm/year*) in places of radar measurements were obtained.

In order to facilitate the presentation and analysis of data on the deformation of the earth's surface, the final information products are rearranged in vector formats SHP for GIS systems and KMZ for software Google Earth. Attribute data contain information about each individual radar measurement (*coordinates, coherence, average vertical displacement speed (mm/year), standard deviation, dynamics of displacements for each shooting date in millimeters relative to the first shooting date, which is the reference point, etc.*).

Deciphering and interpretation of data of multi-pass satellite radar surveys are performed in geographic information system (GIS) ArcGis. Thematic map in raster format was created (Fig. 3). Radar measurements (*vector layers*) on the map are represented by the attribute of the average speed of vertical displacements (*mm/year*). Dots represent the PS method, crosses SBAS method, which are reduced to the color scale of the map legend (*by attribute – average speed of vertical displacements – the authors of the project created color-coded intervals*) and are located on an optical image with a meter spatial resolution (*not relevant in time*). Separately, the dynamics of vertical displacements in the most informative radar measurements was analyzed, which allowed us to determine the main trends in landslides, created graphs. The black contour indicates the area (*landfill*), which is considered man-made.

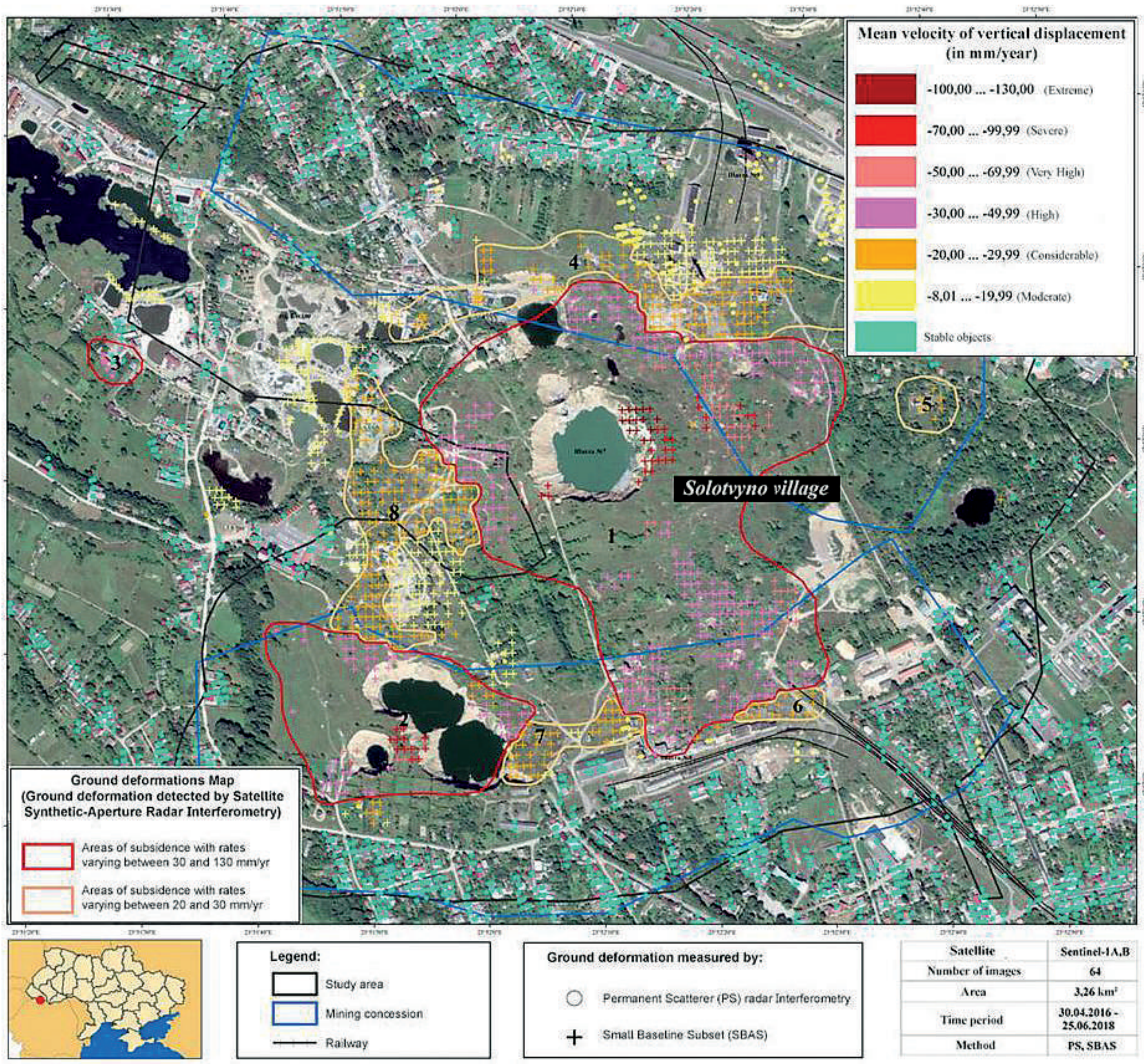

Fig. 3. Thematic map which shows the average speed in places of radar measurements and is divided by intervals according to legend.

Analysis of the obtained results. Based on the thematic analysis of the average velocity of vertical displacements in places of radar measurements, the geodynamic risk zoning procedure was carried out and areas with concentrated deformations of the earth's surface were identified. They were divided into **two categories** by the authors of the work: zone of **intensive** subsidence and zone of **moderate** subsidence. In the category of intensive subsidence, three areas have been identified –Subsidence Zone No. 1, Subsidence Zone No. 2, Subsidence Zone No. 3. In Fig. 3 zones of intensive subsidence are marked by red polygons and black numbers (1, 2, 3), the average subsidence rate is from –30 to –127 mm/year. The largest subsidence of the earth's surface is recorded in the subsidence zone No. 1 and No. 2. They are significant in area and each has a pronounced subsidence trough, where the largest subsidence is defined almost in the center of both zones. At a distance from the center in zones No. 1 and 2, the intensity of subsidence of the earth's surface gradually decreases. According to the authors of the project in the future in these areas may be additional failures of the earth's surface and increase of the existing ones. The territory of the Ruslana Recreation Center, which is located in the subsidence zone No. 3, is dangerous. Sudsidence zones No. 4, 5, 6, 7, 8 are located on the outskirts of subsidence zones No. 1 and No. 2 and are moderate, the subsidence rate is from –20 to –30 mm/year. They are marked in yellow (*polygons*) and black numbers (4, 5, 6, 7, 8). Fig. 3 shows in yellow the places of radar measurements, which have a subsidence rate of –8 to –20 mm/year and on the scale of the authors of the project are defined as “Significant”.

The subsidence zone No. 1 belongs to the category of intensive subsidence and according to the legend of the map, the authors of the work defined it as “threatening-emergency” and has the highest subsidence rate –126 mm/year (Fig. 4). The epicenter of the subsidence is recorded almost in the center of the zone. Geodynamic processes led to the formation of dips in the territory of mine No. 7. It should be noted that the Subsidence zone No. 1 is quite large and the most active in geodynamic terms, it settles at an average rate of –30 mm/year to 127 mm/year.

In the Subsidence Zone No. 1 geodynamic processes (*sedimentation of the earth’s surface*) continue slowly, which creates the preconditions for the deterioration of environmental safety in the study area. According to the authors of the project, new failures of the earth’s surface and an increase in existing ones are possible in the future. Fig. 4 presents the dynamics of subsidence in the most characteristic radar measurements in millimeters. Also, each graph shows the average subsidence rate (mm/year) in this radar dimension.

The subsidence zone No. 2 also belongs to the category of intensive subsidence and according to the map legend, the authors of the work defined it as “threatening-critical” and has the highest subsidence rate –87 mm/year (Fig. 5). The epicenter of the subsidence is recorded almost in the center of the zone. Geodynamic processes have led to the formation of failures.

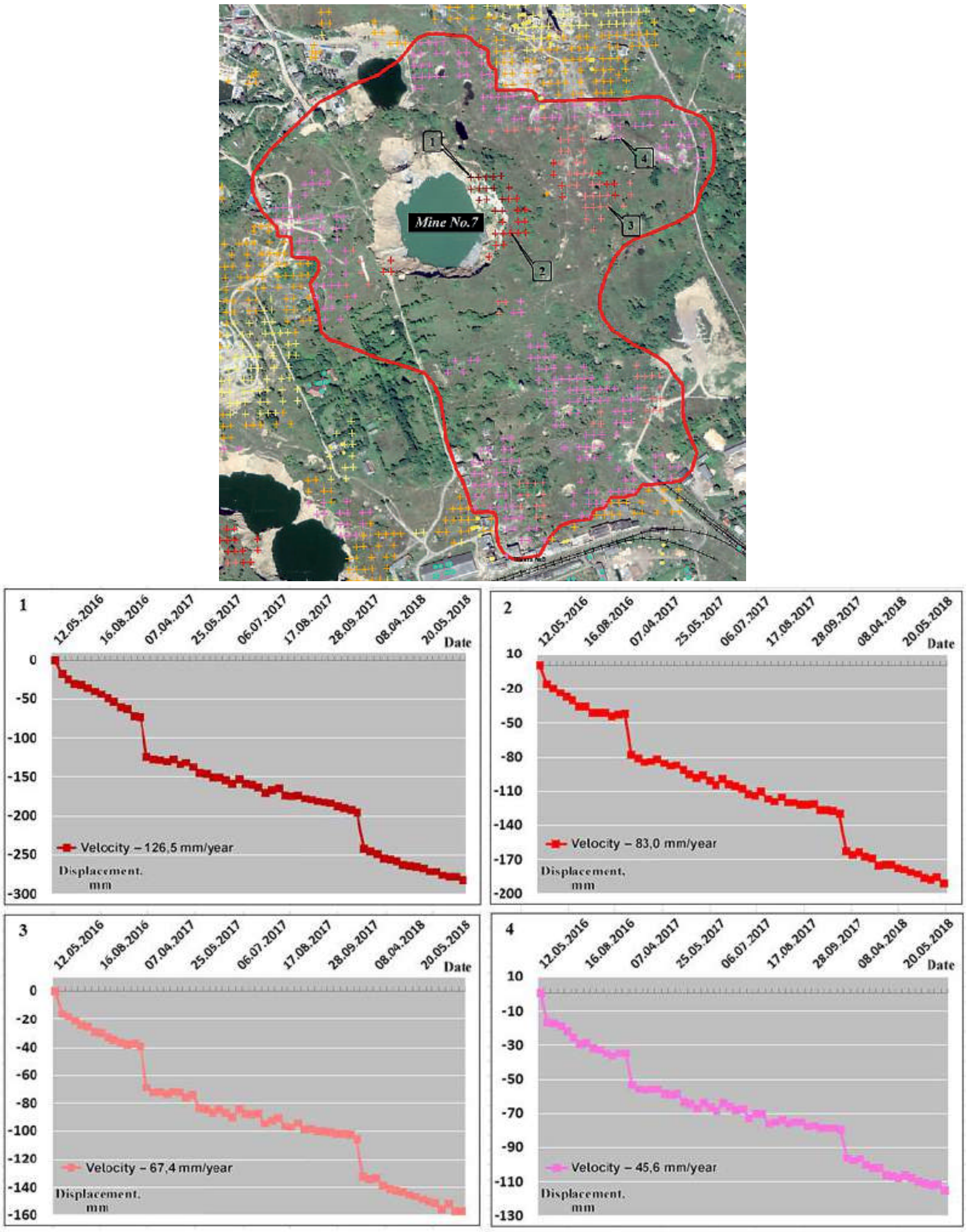

Fig. 4. Subsidence Zone No. 1, graphs of the dynamics of vertical displacements at characteristic points

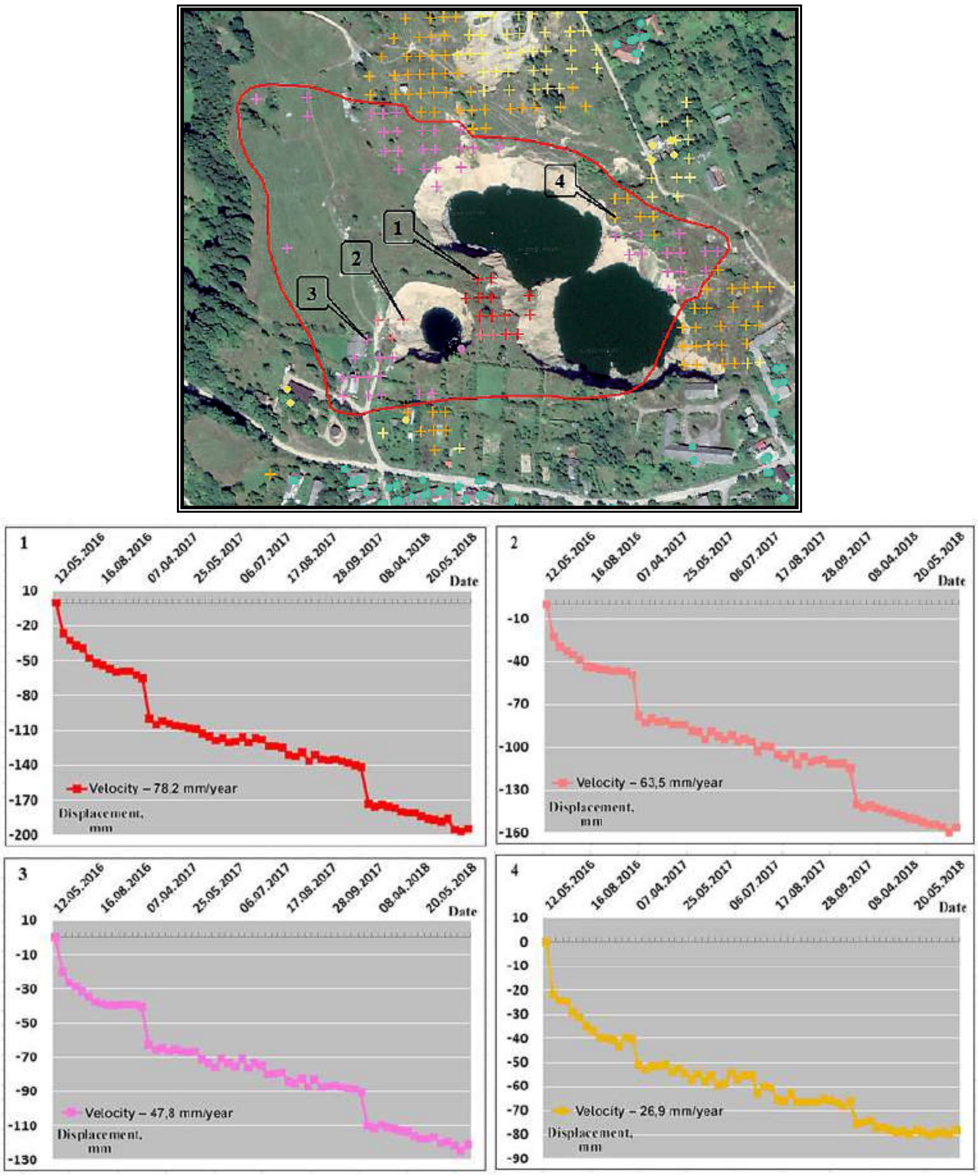

Fig. 5. Subsidence Zone No.2, graphs of vertical displacement dynamics at characteristic points

The subsidence zone No. 2 is the second most geodynamically active subsidence zone in the range of average sedimentation rate from –30 mm/year to –100 mm/year. Geodynamic processes (*sedimentation of the earth's surface*) continue slowly, which creates the preconditions for the deterioration of environmental safety of the area of interest. According to the authors of the project in the future the size of the landslides may increase. Fig. 5 presents the dynamics of subsidence in the most characteristic radar measurements in millimeters, and the graph shows the average subsidence rate (*mm/year*) in this radar dimension.

The subsidence zone No. 3 is defined as "threatening" according to the map legend and has the highest subsidence rate –39 mm/year (Fig. 6).

The Ruslana Recreation Center (Fig. 6) is located in a dangerous area (Subsidence Zone No. 3) and according to the authors of the project in the future subsidence may lead to an emergency situation at its facilities.

According to the results of geodynamic audit of the area of interest for the period from 30.04.2016 to 25.06.2018, a general analytical report was created, which reflects: a list of geodynamically active zones with deformations of the earth's surface and objects located in them (Table 2).

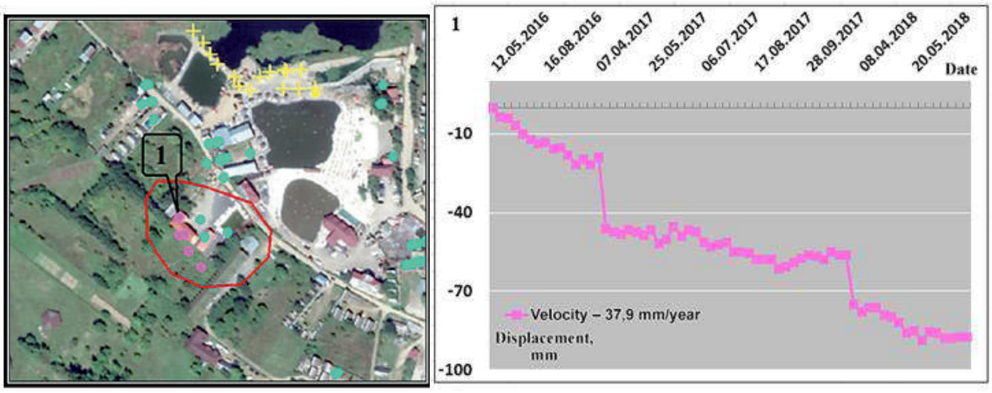

Fig. 6. Subsidence Zone No. 3, graphs of the dynamics of vertical displacements at characteristic points

Table 2

A list of geodynamically active zones with deformations of the earth's surface and objects located in them

No.	Deformation zone title	Title of the object in the subsidence zone	State of the object in the "subsidence zone" according to the authors of the project	The area of the subsidence zone, м^2	Subsidence speed interval, mm/year	Maximum speed of subsidence, mm/year
1	Subsidence zone No. 1	Mine No. 7 and the adjacent territory	threatening-emergency	372962	–30…–126	126
2	Subsidence zone No. 2	Narodna Str. (northern part)	threatening-critical	104689	–30…–100	87
3	Subsidence zone No. 3	Ruslana Recreation Center	threatening	6050	–30…–50	39
4	Subsidence zone No. 4	Eldorado Recreation Center, territory of the mine No. 9, southern part of the territory of product market	dangerous	77599	–20…–30	31
5	Subsidence zone No. 5	Nachiku shop	dangerous	8989	–20…–30	27
6	Subsidence zone No. 6	Eastern part of Mine No. 8	dangerous	6614	–20…–30	29
7	Subsidence zone No. 7	Western part of Mine No. 8	dangerous	16287	–20…–30	29
8	Subsidence zone No. 8	Territory to the west from Mine No. 7	dangerous	55721	–20…–30	29

The results of the independent geodynamic audit of the objects and territories of the mining and chemical enterprise Solotvynsky Salt Mine were obtained using an alternative method of observation, namely space radar tools and methods. In the period from 04.30.2016 to 06.25.2018, the chronology of subsidence of soils and objects in time was studied. According to the audit, the following zones were identified: zones of concentrated deformations of the earth's surface in the range of average subsidence rate from –30 to –130 mm/year (*zoning of the territory according to the degree* of geodynamic risk – ***intensive** and **moderate** subsidence*); the dynamics of subsidence in the characteristic radar measurements was analyzed; the objects which have got to a technogenic-dangerous zone were investigated.

The results of interferometric processing of radar survey data were confirmed by means of high-precision geometric leveling (***high agreement of measurement results of objects' vertical displacements by interferometric and geodetic** methods is observed*). Both methods confirmed the presence of zones of active subsidence on the territory of mining. It was determined that in fact, the entire research area is man-made and threatening Solotvyno, with the exception of its outskirts in the north and south and has two pronounced subsidence troughs located in the subsidence zones No. 1 and No. 2.

The analysis confirms the need to adapt the existing method of deformation monitoring using space radar interferometry in relation to the territories of the liquidated mines of mining and chemical enterprises and other objects, taking into account the specifics of the resulting deformations of the earth's surface. This technology, being integrated into the classical system of surveying and geodetic observations, will allow us to regularly obtain models of vertical landslides in large areas and will significantly reduce the cost of obtaining such data. And with a comprehensive approach it will allow to verify and refine the data bygeodetic methods and tools. Timely organized observations allow timely forecasting and assessment of the nature and safety degree of the situation and recommend protection measures.

Thus, depending on the location of man-made area on Earth, the impact of geodynamic processes can be manifested at the global, regional or local levels. The emergence of new geodetic and geotechnical devices allows the creation of comprehensive monitoring systems of man-made areas. The use of the results of geotechnical observations in combination with the results of geodetic measurements requires the development of methods for the joint processing of such results and its verification on real objects.

To systematize, process and analyze data on the conditions of development and activation of exogenous geological processes (landslides, karst, flooding, abrasion and mudslides), we propose to create an automated information system "Exogenous geological processes". The main tasks of the system are collection, accumulation of information on the conditions of development of exogenous geological processes.

Conclusions

1. The existing problems of deformations monitoring of the earth's surface by geodetic methods at underground development of mineral deposits are defined.The necessity of the complex approach application to its performance on the basis of modern ground and remote methods usageis substantiated. Features of the method of space radar interferometry and its main advantages over other surveying and geodetic methods of observations are described.

2. By means of satellite radar survey and interferometric methods of data processing the influence of mineworkings of Solotvynsky Salt Mine SE on the earth's surface, buildings and structures (*geodynamic audit for the period from 30.04.2016 to 25.06.2018 was carried out)* is investigated. By the method of geometricleveling the obtained resultsare verified. It is proved that abandoned salt mines pose a significant threat to thevillage of Solotvyno.

3. The relevance of the use of space radar interferometry in the system of complex deformation monitoring of forged territories, in particular at the stage of liquidation of minefields, in accordance with the existing requirements for measurements is substantinated.

4. In order to eliminate and monitor the dangerous situation in Solotvyno, the results will be used for environmental rehabilitation and development of the territory as well as the establishment of a monitoring system.

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ДОСЛІДЖЕННЯ ВПЛИВУ ГІРНИЧИХ ВИРОБОК РУДНИКІВ ДП “СОЛОТВИНСЬКИЙ СОЛЕРУДНИК” НА ЗЕМНУ ПОВЕРХНЮ, БУДІВЛІ ТА СПОРУДИ З ВИКОРИСТАННЯМ СУПУТНИКОВОГО РАДАРНОГО МОНІТОРИНГУ

Дослідження спрямовані на проведення геодинамічного аудиту ДП “Солотвинський солерудник” та прилеглої території з можливістю виявлення зон із осіданням або підняттям земної поверхні, які плавно сповільнюються, прискорюються або розвиваються із постійною швидкістю. Для моніторингу зони інтересу використано сучасні технології супутникової радарної інтерферометрії. Достовірність отриманих результатів підтверджено вимірюваннями вертикальних зміщень земної поверхні та окремих об’єктів методом геометричного нівелювання. За результатами спостережень величин зсувів земної поверхні та окремих об’єктів космічними (радарної інтерферометрії) та наземними (геометричним нівелюванням) методами зафіксована висока кореляція даних і підтверджена наявність зон активних осідань на території гірничої виробки. До найнебезпечніших екзогенних геологічних процесів (ЕГП) за величиною збитків, завданих господарським об’єктам, належать: зсуви, карст, підтоплення, абразія, селі тощо. Поширення та інтенсивність прояву ЕГП визначаються особливостями геологічної та геоморфологічної будови території, її тектонічним, неотектонічним та сейсмічним режимами, а також гідрологічними, кліматичними, гідрогеологічними палео- та сучасними умовами. Солотвинський солерудник – одне із найстаріших підприємств Закарпаття. Родовище експлуатується із часів Римської імперії. У 1360 р. на місці рудника було засновано поселення солекопів – Солотвино, яке згодом стало центром солевидобування і королівською монополією. Загалом на родовищі пройдено дев'ять шахт. У 1995–1996 та 2001 роках після паводків почалося затоплення шахт. У 2005 р. в Солотвині активізувалися зсувні та карстові провалля, що призвело до пошкодження житлових будинків, доріг та інфраструктури. Повністю затоплено дві шахти. Сьогодні на території солерудника і прилеглих територіях спостерігаються небезпечні природні та техногенні процеси. Це переважно соляний карст, як підземний, так і поверхневий, провали територій у місцях розташування шахт, а також зсувні процеси. Тому мета досліджень – здійснення геодинамічного аудиту ДП "Солотвинський солерудник" та прилеглої території з можливістю виявлення зон із осіданням або підняттям земної поверхні, які плавно сповільнюються, прискорюються або розвиваються із постійною швидкістю. Для досліджень та виконання геодинамічного аудиту ДП "Солотвинський солерудник" та прилеглої території використано дані радіолокаційної інтерферометрії із 30.04.2016 до 25.06.2018 р. У роботі використано сучасні методи інтерферометричного оброблення супутникових радіолокаційних даних: метод "PS" – метод постійних розсіювачів та метод SBAS – метод малих базових ліній. Методом геометричного нівелювання здійснено вимірювання вертикальних зміщень в окремих місцях земної поверхні з метою верифікації інтерферометричних даних. Моніторинг зони інтересу проведено із використанням сучасних технологій супутникової радарної інтерферометрії. За результатами спостережень величин зсувів земної поверхні та окремих об'єктів космічними (радарної інтерферометрії) та наземними (геометричним нівелюванням) методами зафіксовано високу кореляцію даних і підтверджено наявність зон активних осідань на території гірничої виробки.

Ключові слова: ДЗЗ; радарна інтерферометрія; вертикальні зміщення земної поверхні; методи PS та SBAS; геометричне нівелювання; моніторинг.
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